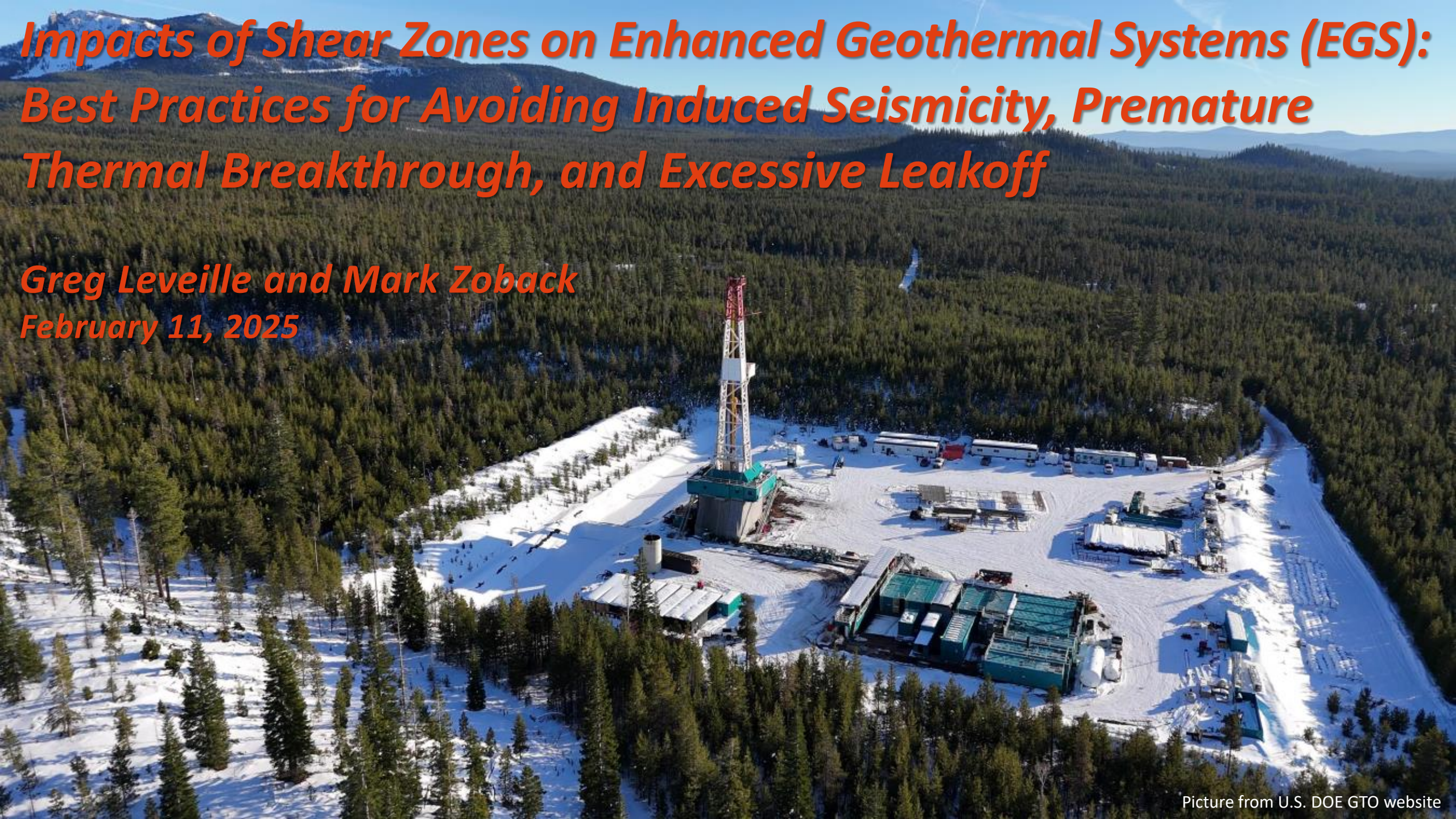
Impacts of Shear Zones on Enhanced Geothermal Systems (EGS): Best Practices for Avoiding Induced Seismicity, Premature Thermal Breakthrough, and Excessive Leakoff

Greg Leveille and Mark Zoback

February 11, 2025



Picture from U.S. DOE GTO website

Questions to be addressed

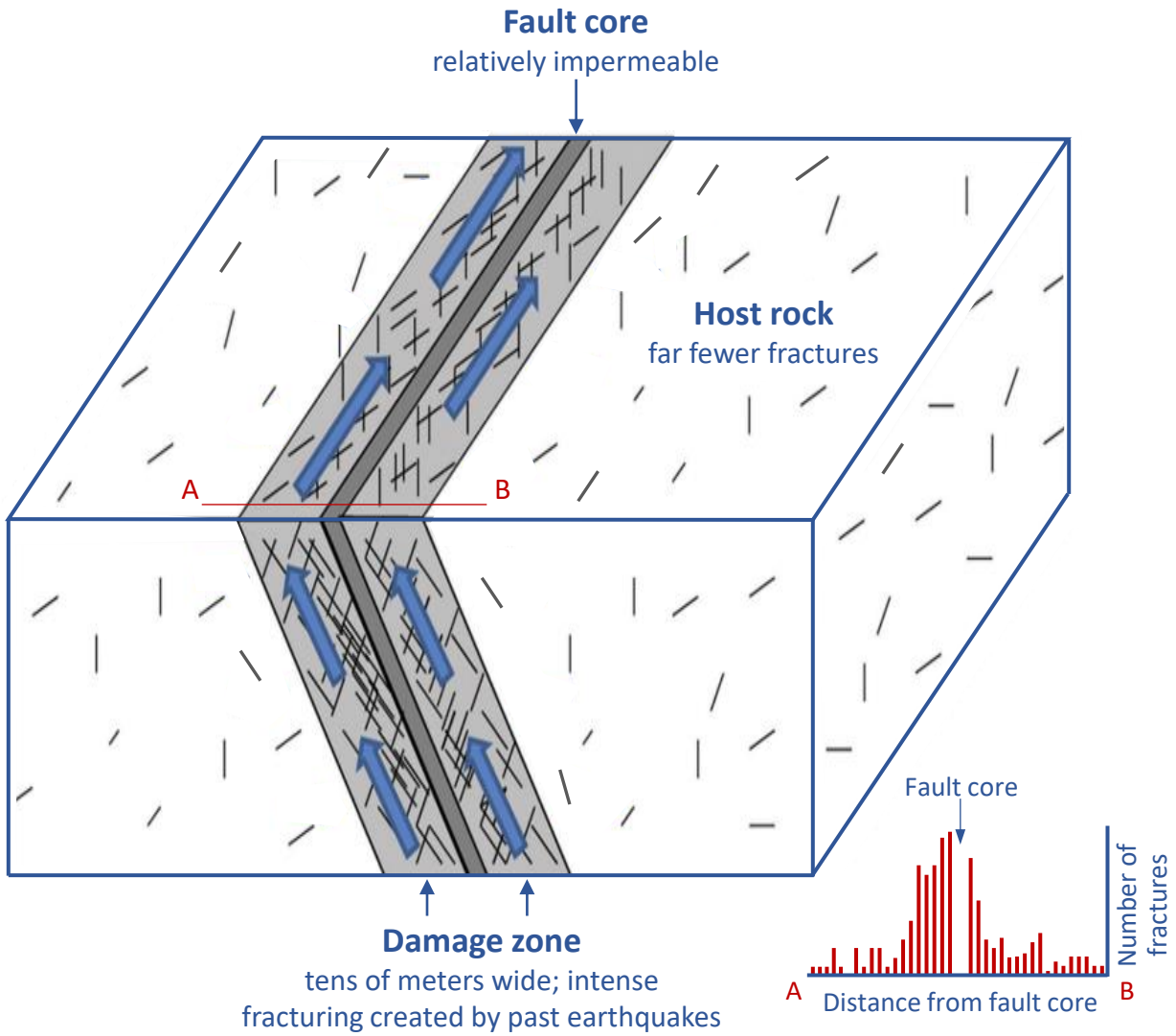
- What shear-zone-related attributes threaten the success of an otherwise ideal EGS prospect that is to be developed with hydraulically fractured horizontal wells?

- Is there a way to optimally phase operations to resolve the fundamental challenge of often not knowing if problematic shear-zones exist within a prospective area?

- What actions can be taken to mitigate negative economic impacts if problematic shear zones are encountered in a development area?

Structural and flow potential characteristics of shear zones

Damage zones can be pervasively fractured



Main figure after Johri et al. (2014), inset after Gudmundsson (2022)

Critically stressed fractures in damage zones

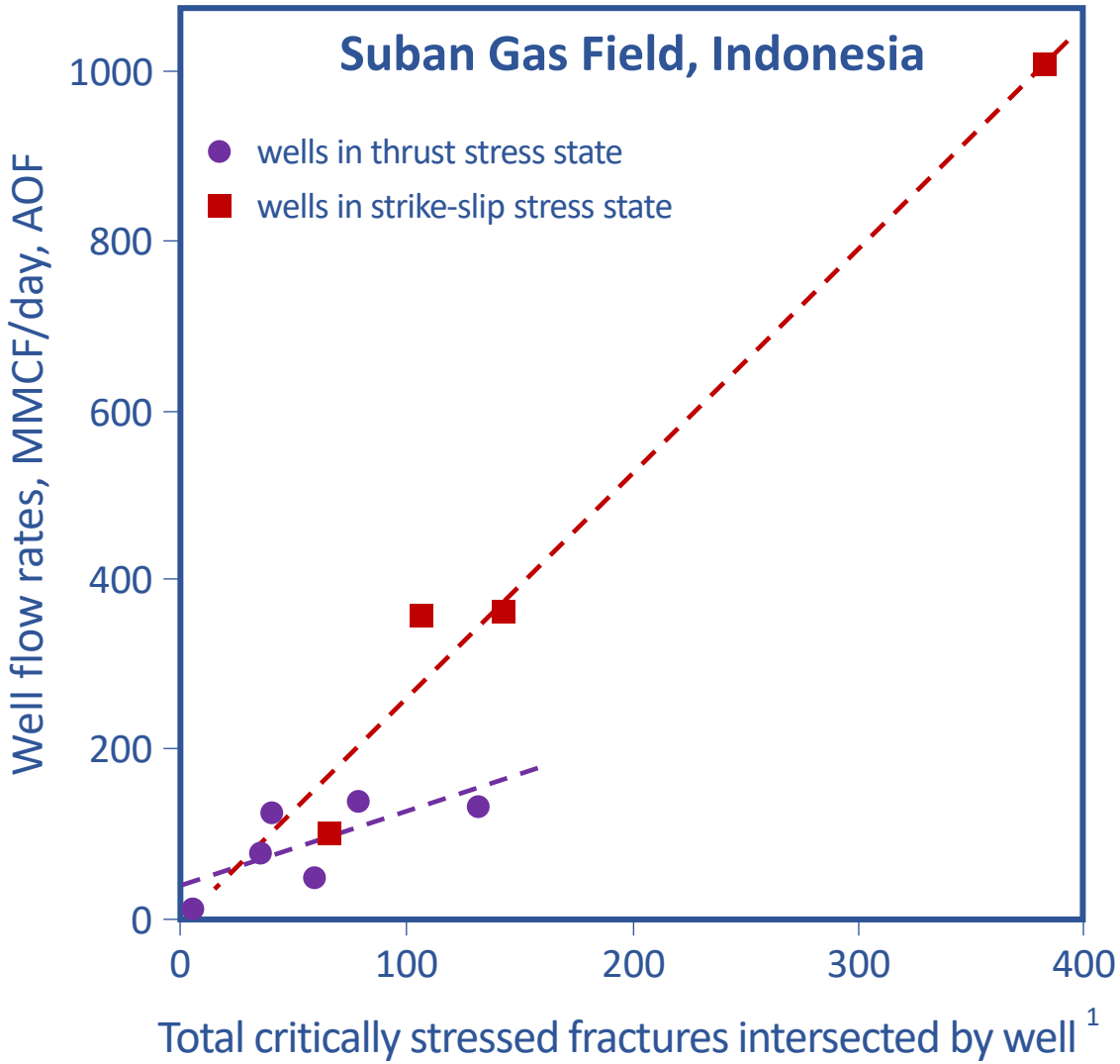


Figure after Hennings et al. (2012). MMCF = million cubic feet, AOF = absolute open flow, [1] from image logs.

Outcomes from hydraulically fracturing critically stressed shear zones

Faults can hijack hydraulic fracturing stages

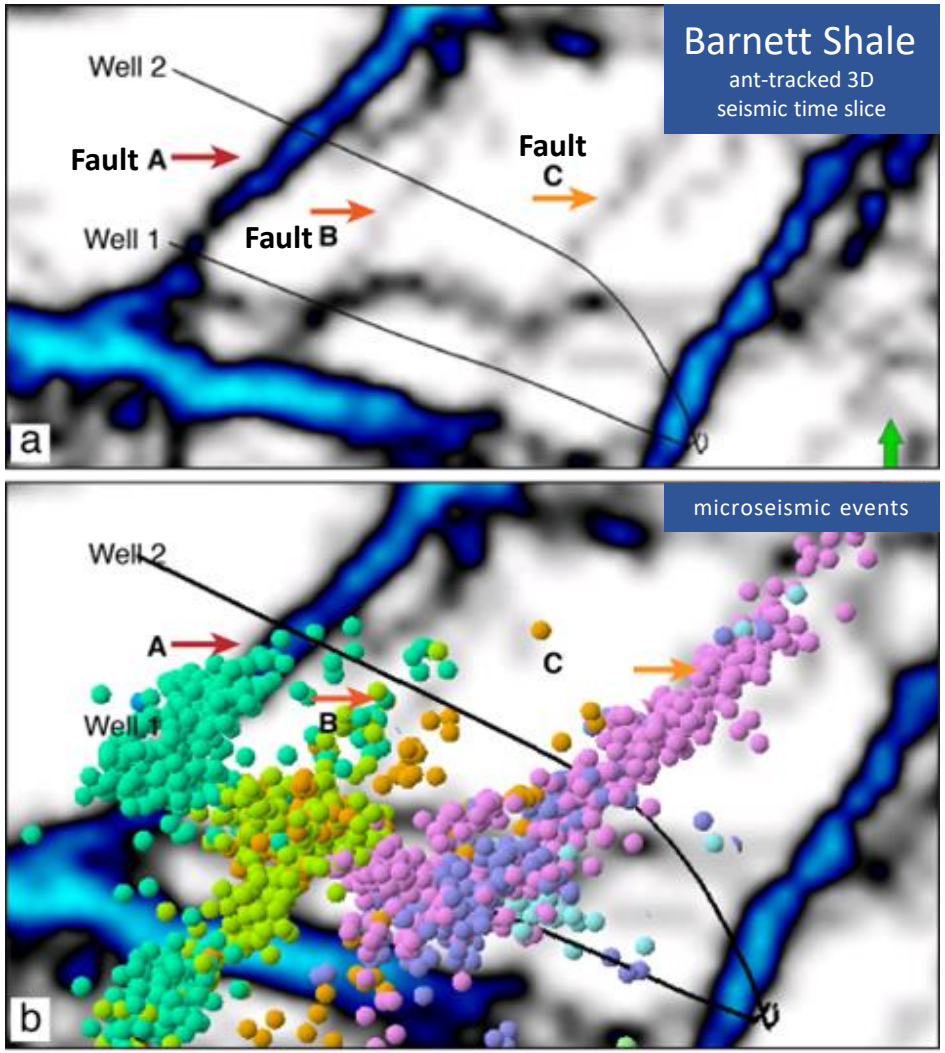


Figure after Farghal and Zoback (2016)

Hydraulic fracturing can induce seismicity

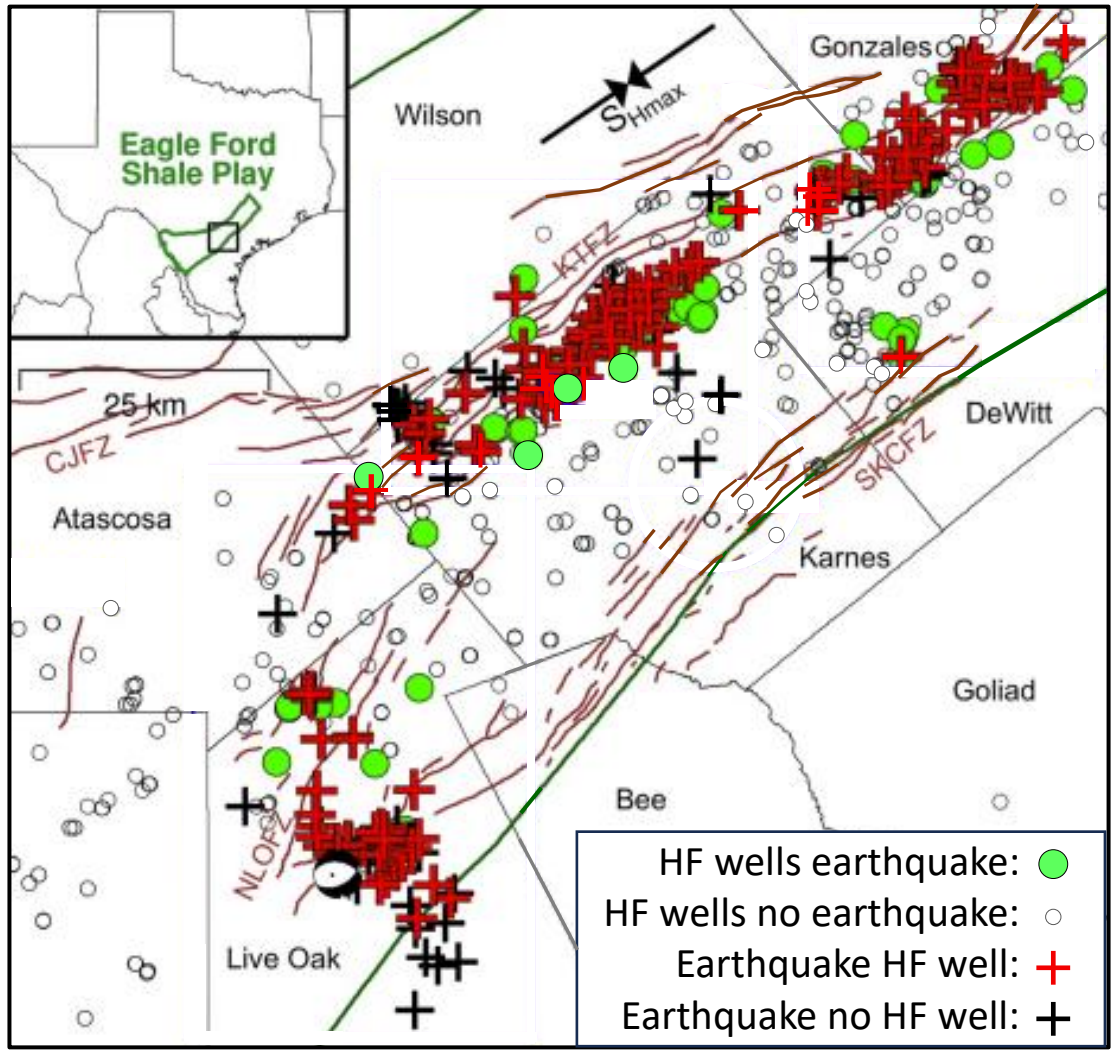
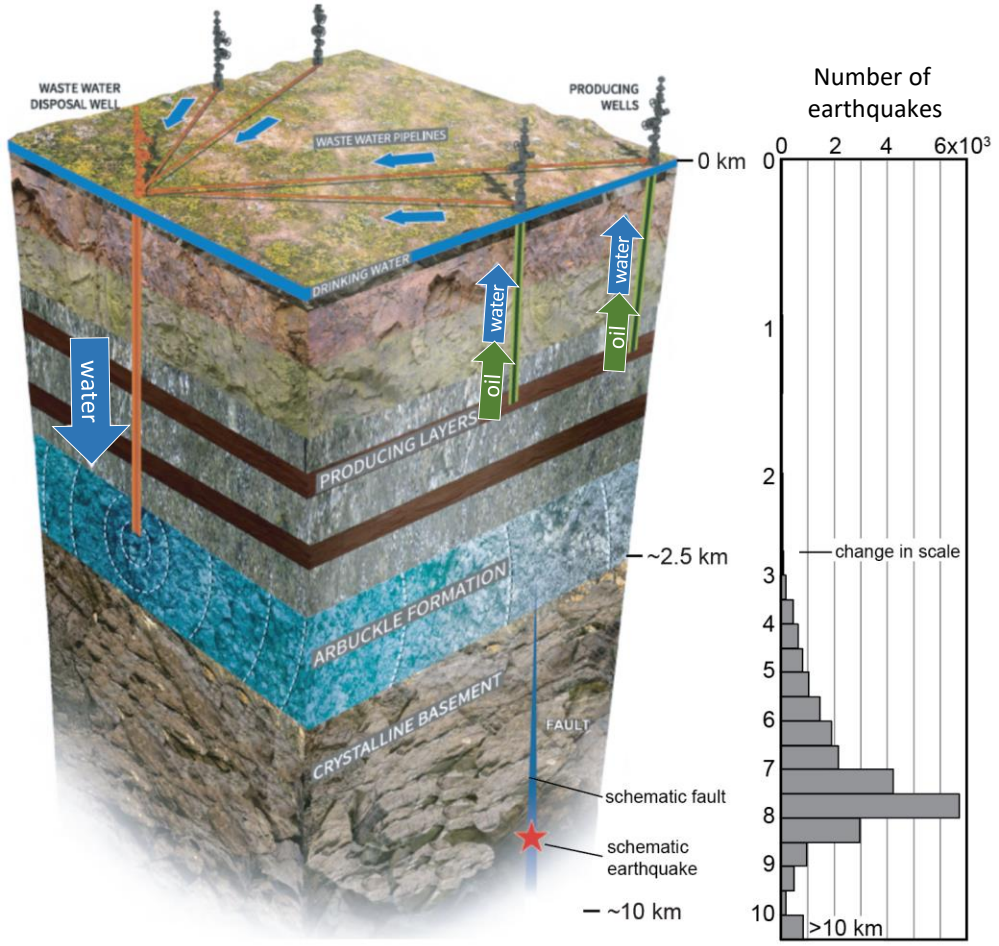


Figure after Fasola and Brudzinski (2022); HF = hydraulically fractured; Earthquakes up to Mw 4.8 induced by HF

Oil field produced water disposal has activated critically stressed basement faults



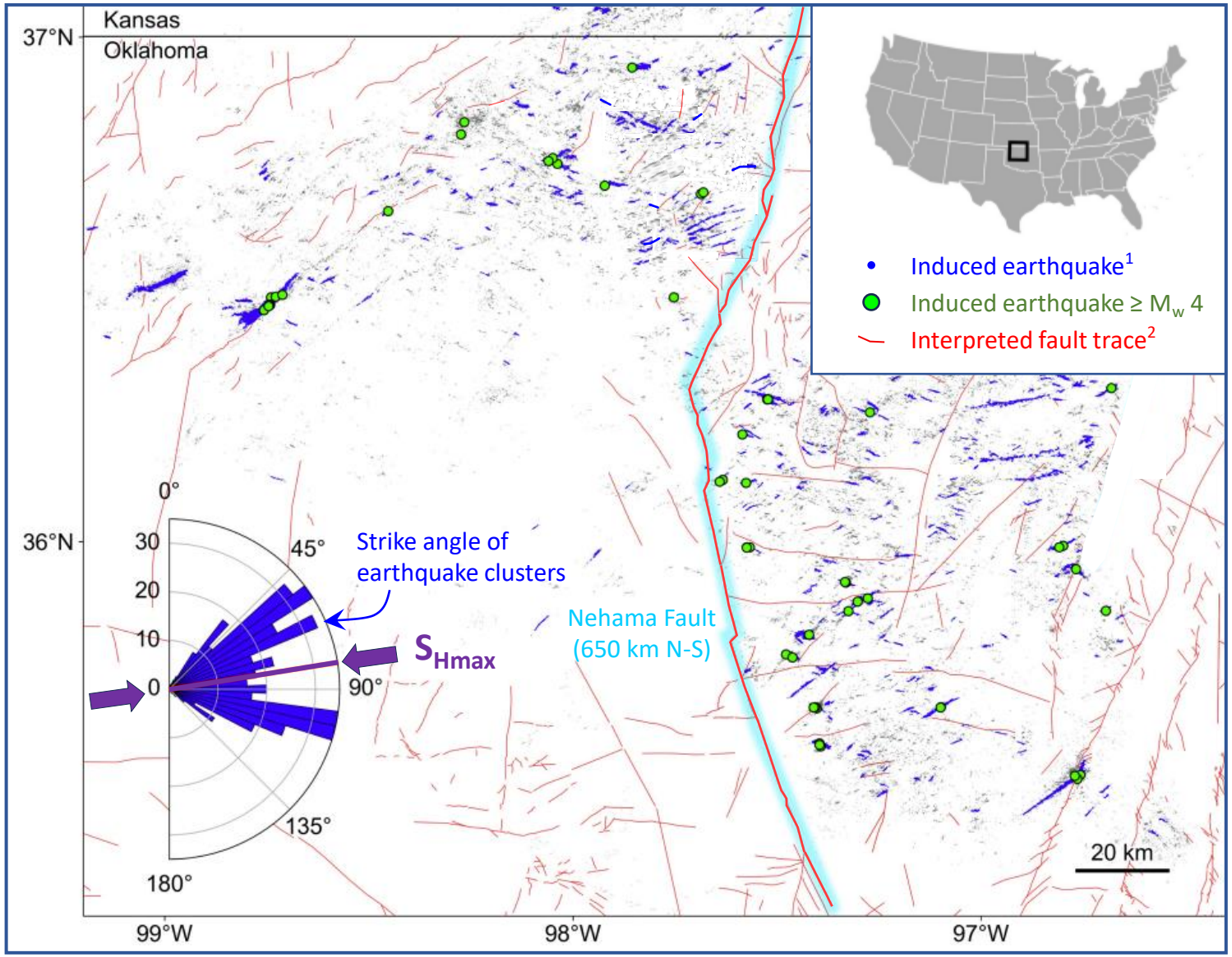
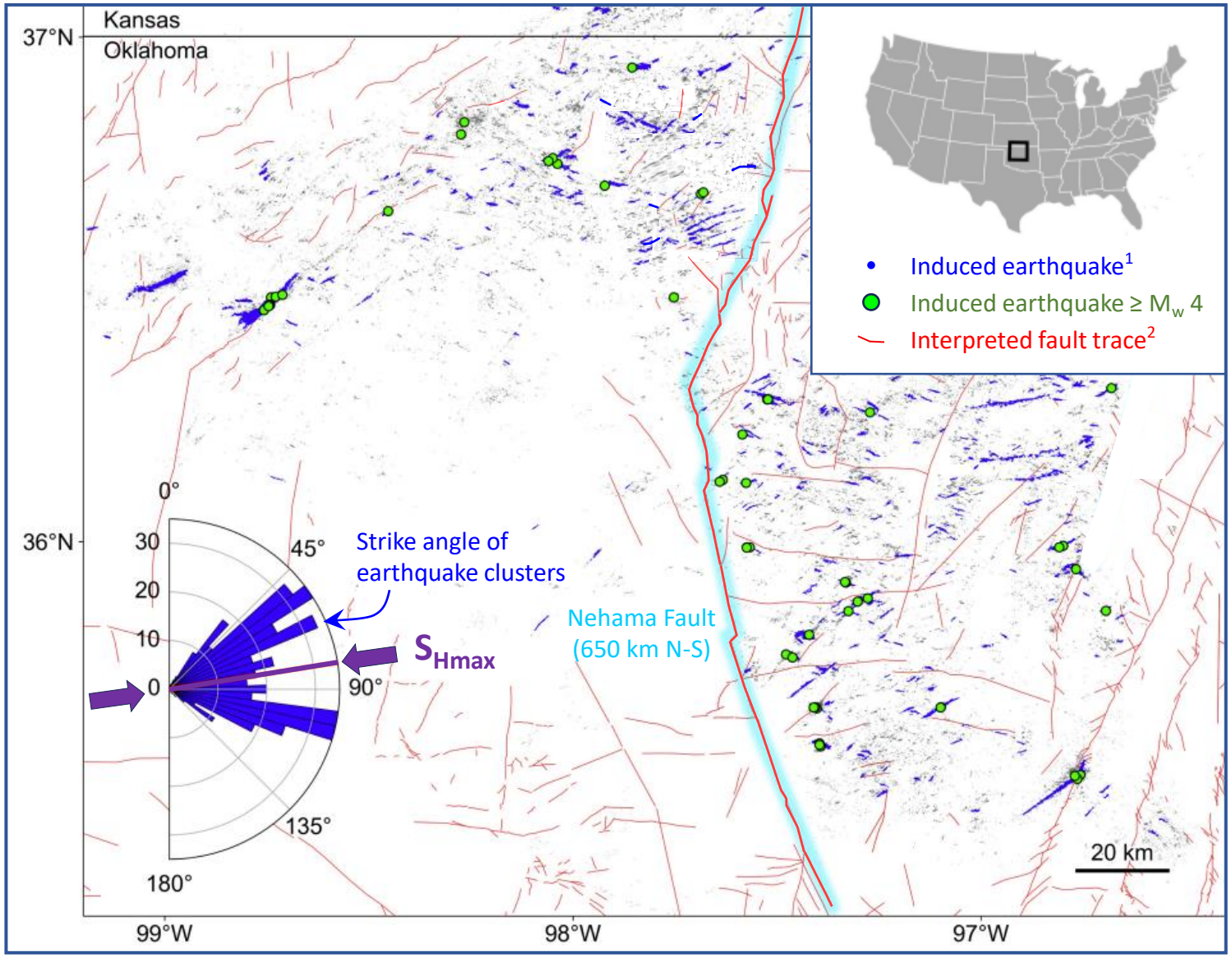


Diagram on left from Zoback and Kohli (2019); Figure on right modified after Park et al. (2022); [1] Earthquakes that belong to clusters with sufficient scale to host a Mw ≥ 4 event shown by blue dots, rest by gray dots; [2] from Marsh and Holland (2016)

The current stress field defines which fault orientations are potentially active

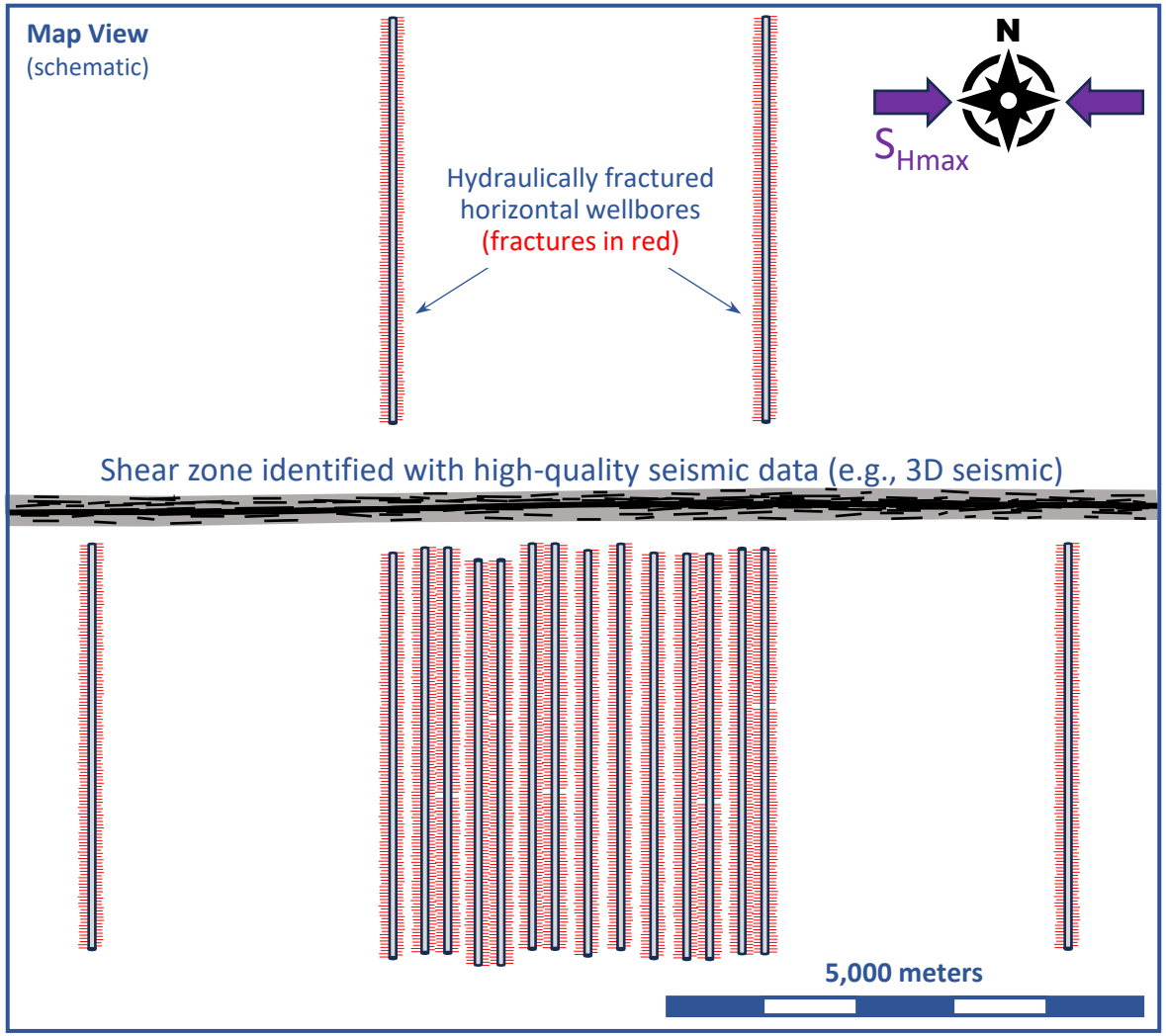


- ≈ 400,000 earthquakes induced by an ≈ 1 MPa pressure change in the Arbuckle Formation; events up to M5.8; $S_{Hmax} \geq S_V > S_{hmin}$
- Favorably-oriented faults in crystalline basement rocks are in frictional failure equilibrium
- Faults not favorably oriented relative to the current stress field did not fail
- Few of the faults in the crystalline basement rocks that failed were recognized prior to failure

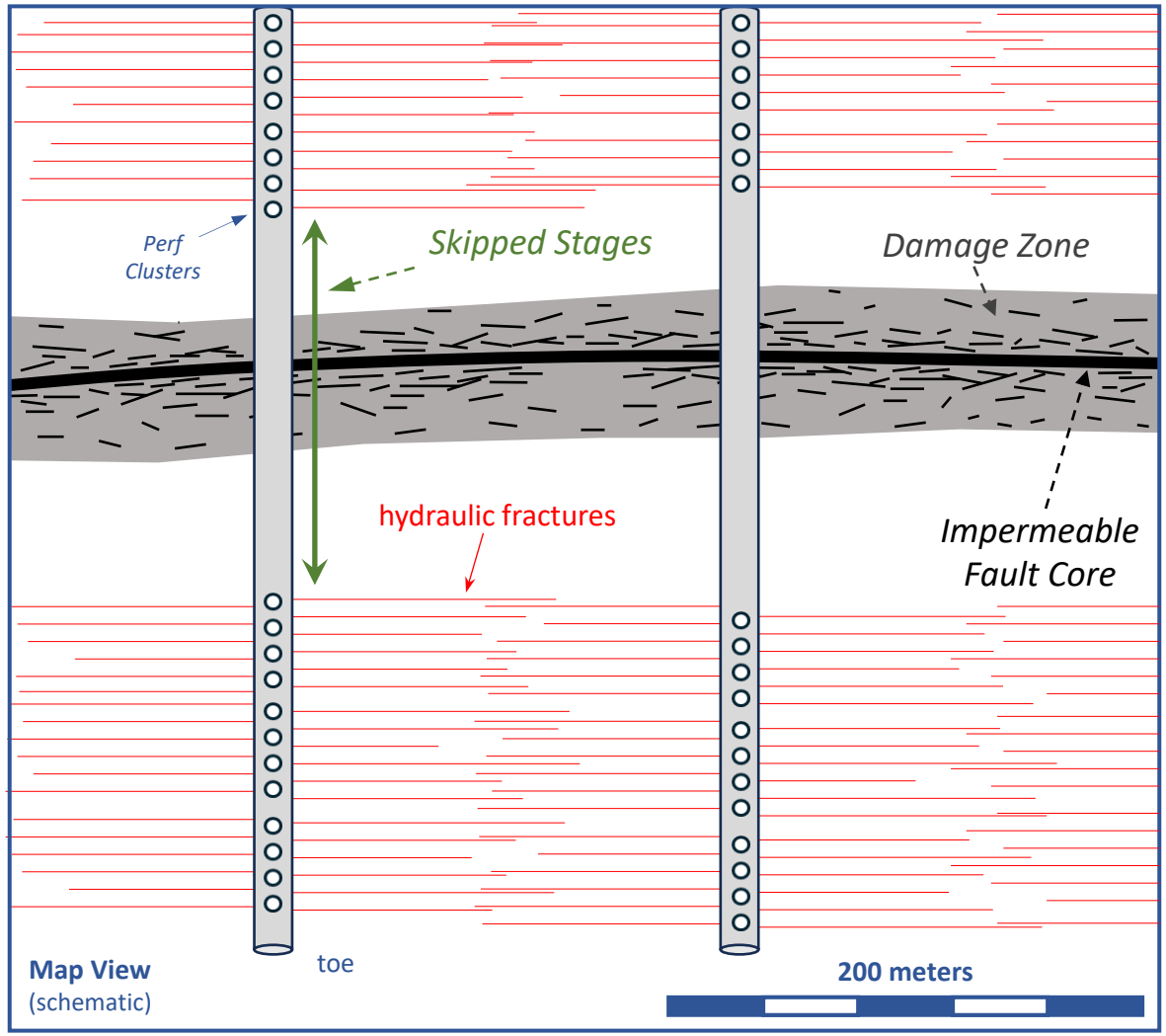
Figure modified after Park et al. (2022); [1] Earthquakes that belong to clusters with sufficient scale to host an Mw ≥ 4 shown by blue dots, rest by gray dots; [2] from Marsh and Holland (2016)

O&G industry approach to problematic shear zones[1] – detect and avoid

Avoidance via well placement



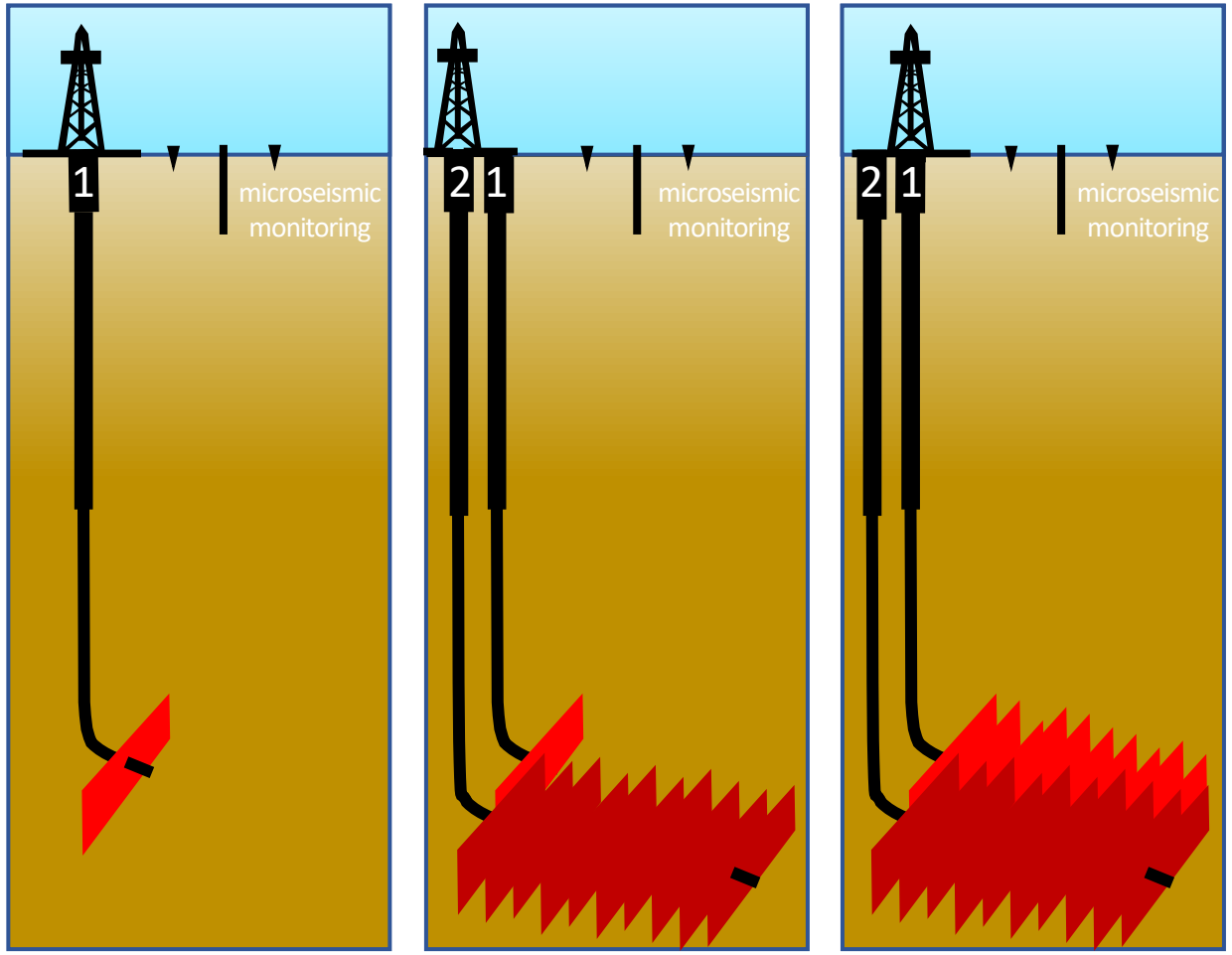
Avoidance by skipping frac stages



[1] That is, problematic shear zones in areas being developed using hydraulically fractured horizontal wells (e.g., the Eagle Ford play in south Texas and Montney play in British Colombia)

For EGS in crystalline rocks, operations should be phased to detect shear zones

Haute-Sorne project, Switzerland



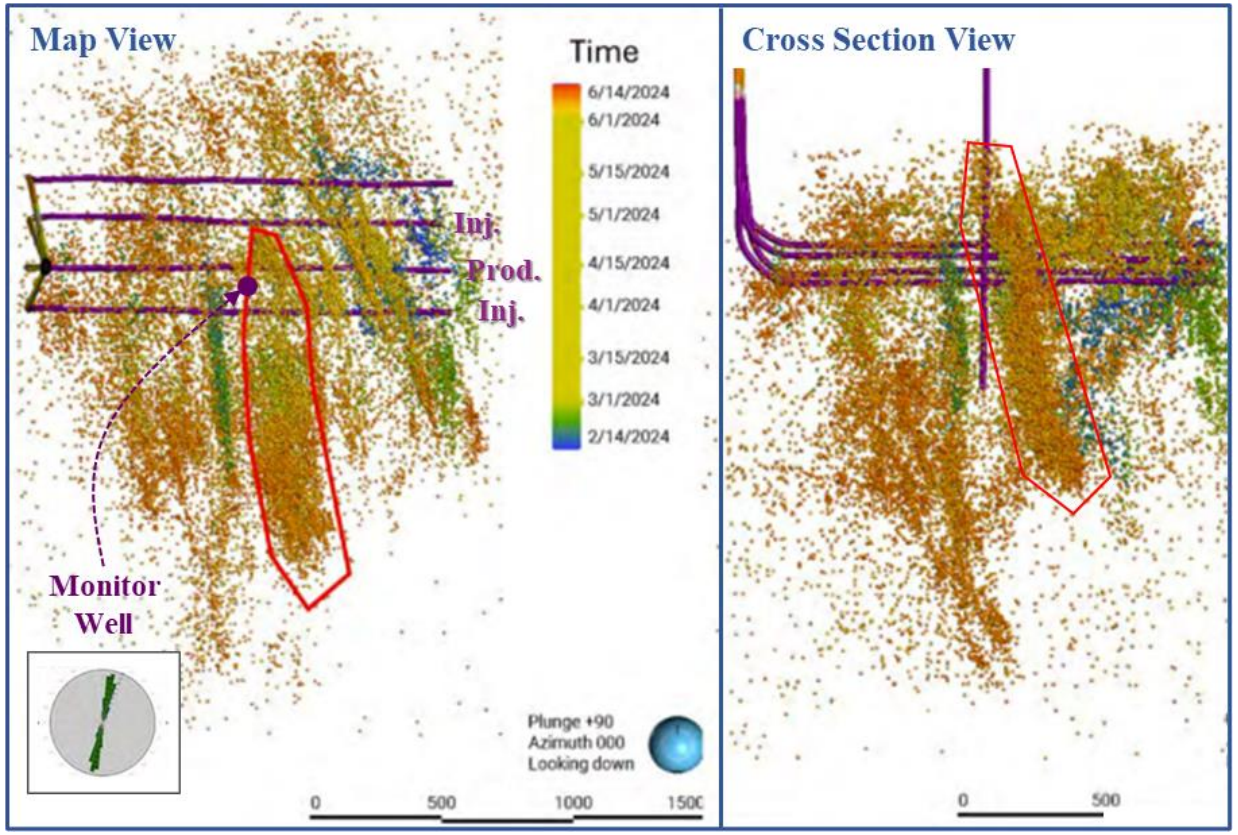
Drill, Frac, Assess Data

Drill, Frac, Assess Data

Drill, Frac, Assess Date, Produce

Figure simplified from one included in Meier et al. (2024)

Cape Station project, Utah USA



Hydraulic fracturing performed on three of first four wells drilled, followed by a thirty-day flow test (max. rate 70,000 bwpd)

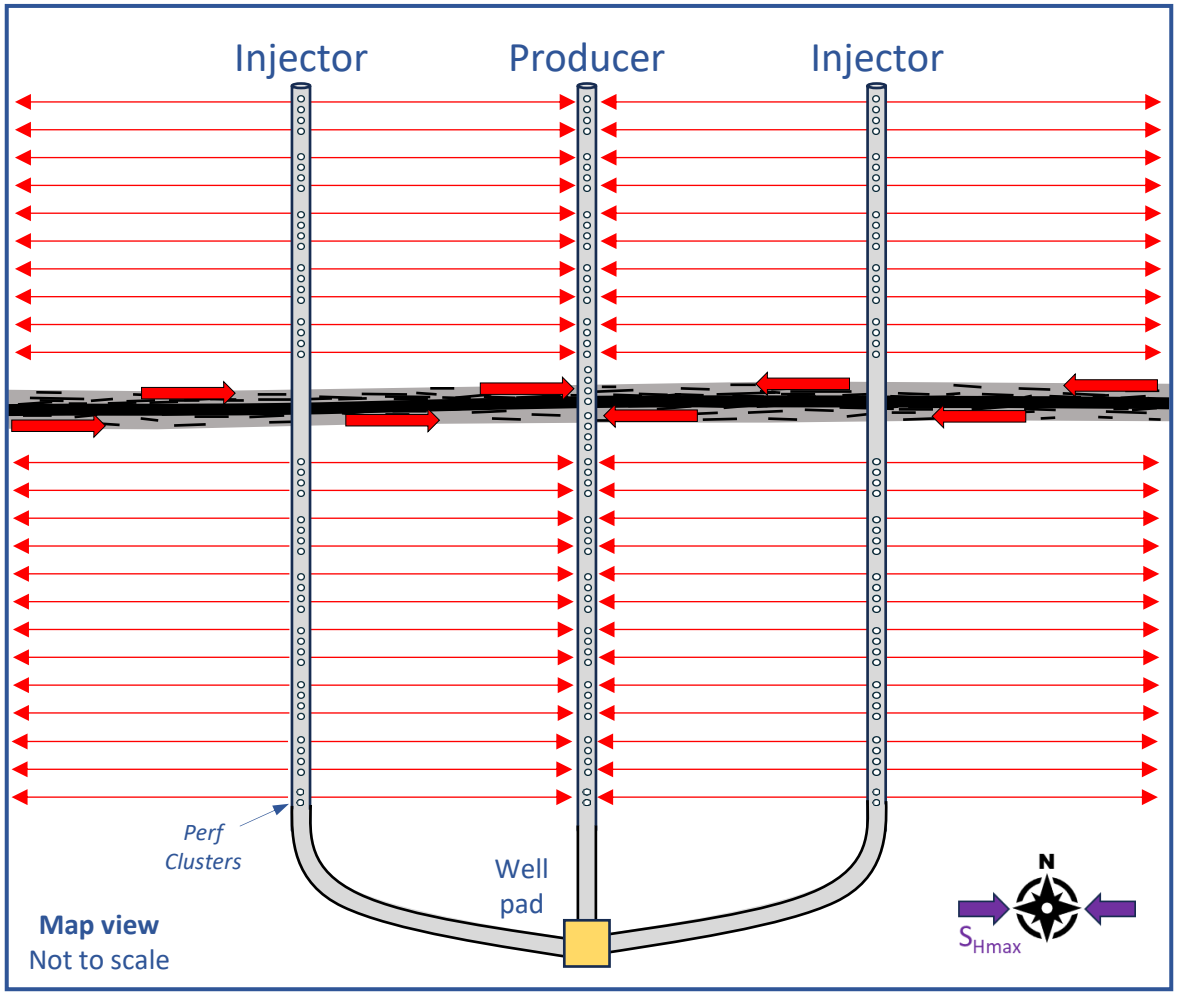
Figures slightly modified after Dadi et al. (2024)

Acquiring data about shear zones early on is essential for maximizing project value

Probability-weighted value maximization[1]

- Avoid penetrating critically stressed shear zones with wells
- Skip frac stages in all wells that penetrate critically stressed shear zones
- Skip frac stages in only injection wells (see figure on the right)
- Fracture everything; attempt to shut-off problematic zones if negative outcome

Combined EGS / hydrothermal production

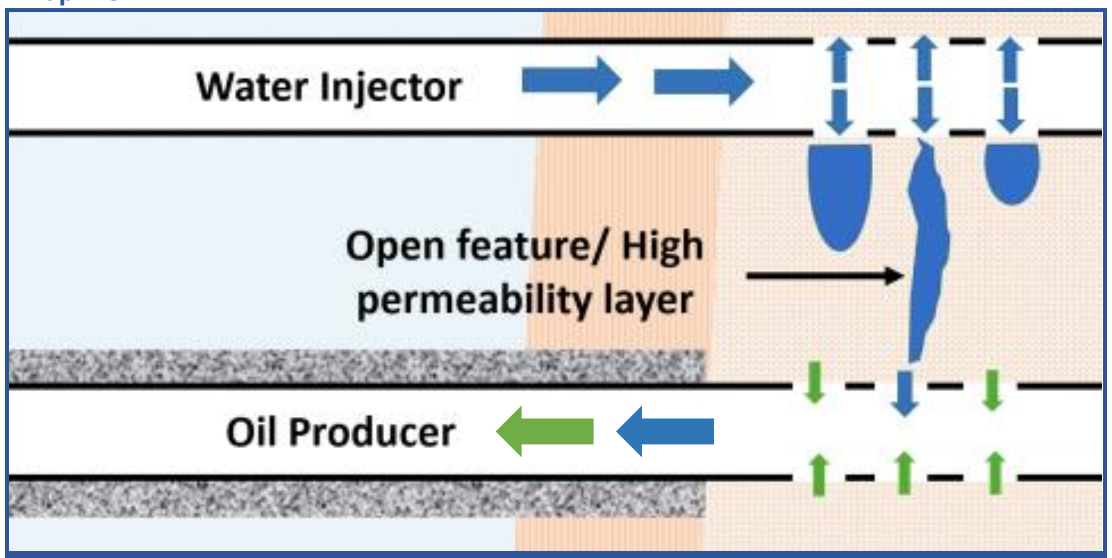


Potential unintended consequence - Perfing producers could create cross-flow risk

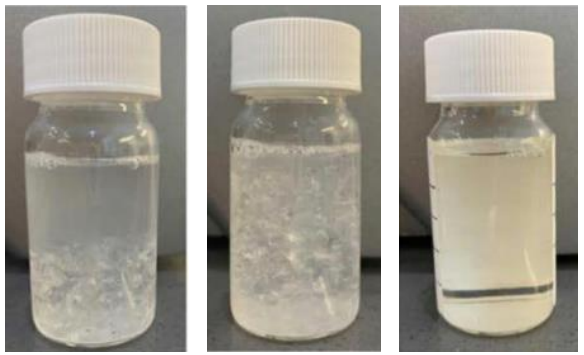
[1] Actions listed from least risky to most risky; conversely, actions are listed in inverse order as far as potential upside

Shutting off problem zones can be problematic

Map View



Initial challenge – diagnosing cause of the problem



Initial Condition | Fully Swollen | Fully Bonded

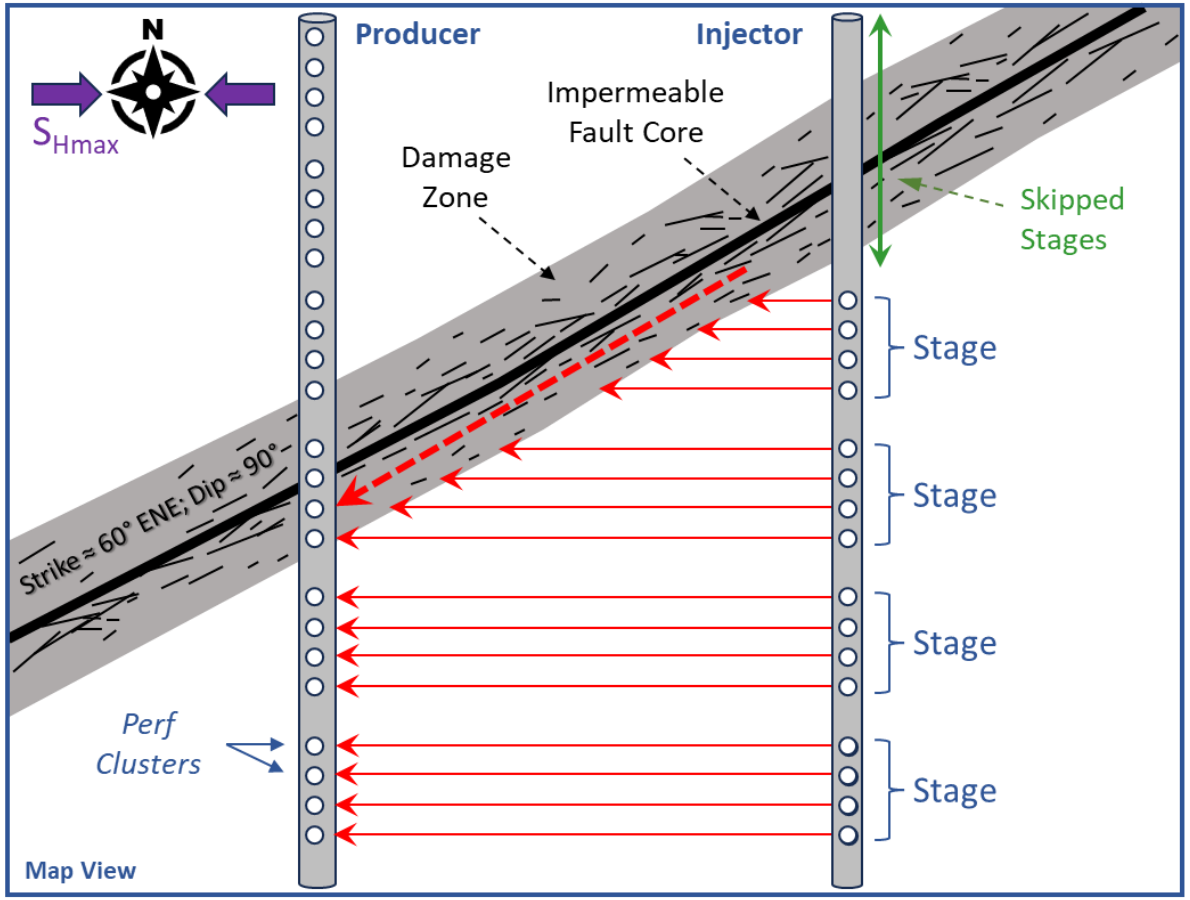
Oil and gas industry solutions

- Mechanical devices, plugging agents, chemical treatments
- Pre-installed or deployed later
- Inflow, outflow, or both
- Challenges abound:
  - Cost, reliability, effectiveness
  - Harsh operating environments
  - Limited diagnostics; impaired "vision"
- Problem avoidance value is non-trivial

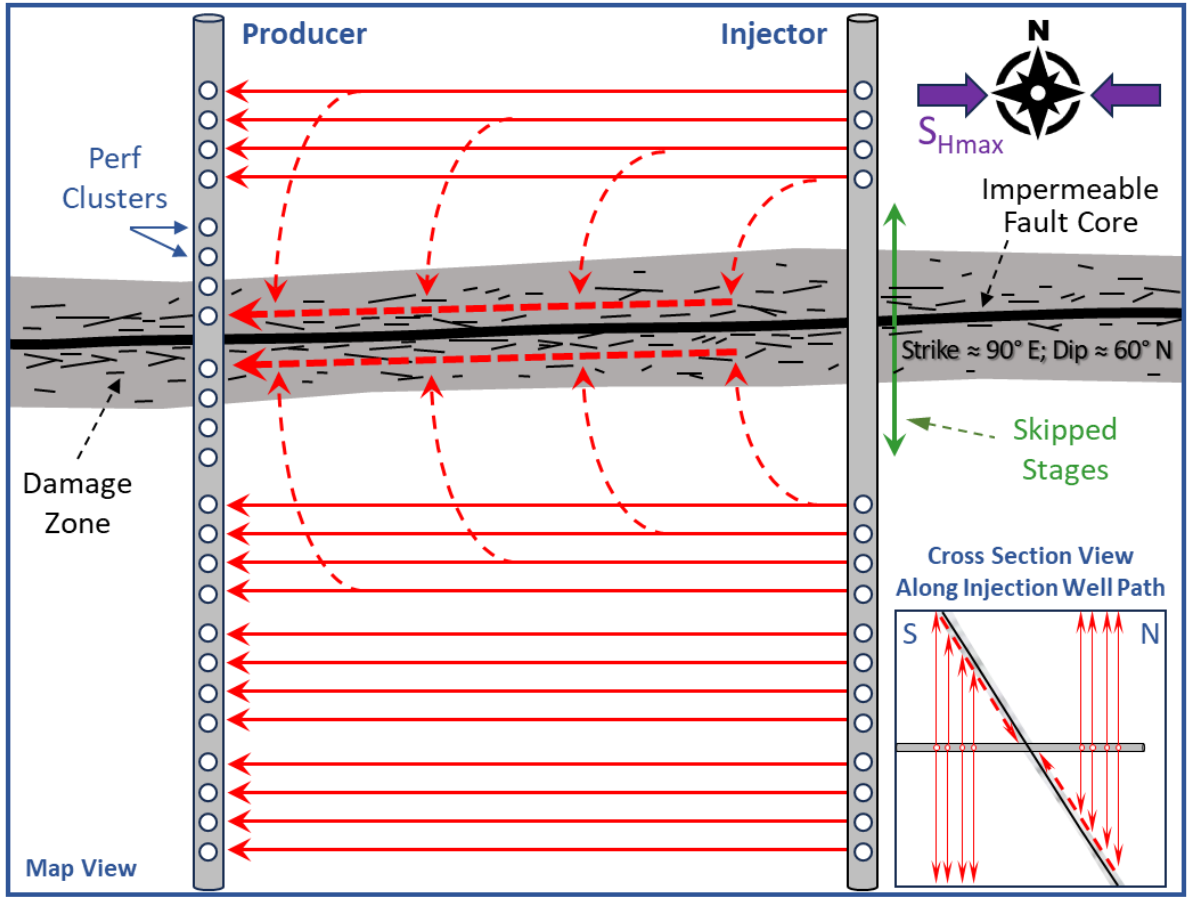
Figure at top from Taha and Amani (2019); bottom left picture from Sun and Bai (2017); pictures on bottom right from Targac et al. (2020)

Hybrid pathways[1] can concentrate flow and lead to problems

Strike Slip Displacement



Normal Displacement



[1] Hybrid pathways = pathways in which flow occurs both within hydraulic fractures and the damage zones of critically stressed faults. To simplify the diagram, only a few of the many flow paths leading out from the injection wells are shown.

Impact of shear zones on EGS: key take-away messages

- Avoiding critically stressed shear zones is crucial for optimizing EGS developments with multi-stage hydraulically fractured horizontal wells
- Shear zones favorably oriented to fail in the current stress field should be considered as potentially active faults
- As shear zones are nearly impossible to detect geophysically in crystalline basement rocks, operations should be phased so that microseismic, fiber optic and other data can be acquired in appraisal wells before moving into full development
- If critically stressed shear zones are encountered, employing a probability-weighted risk management approach can help maximize value

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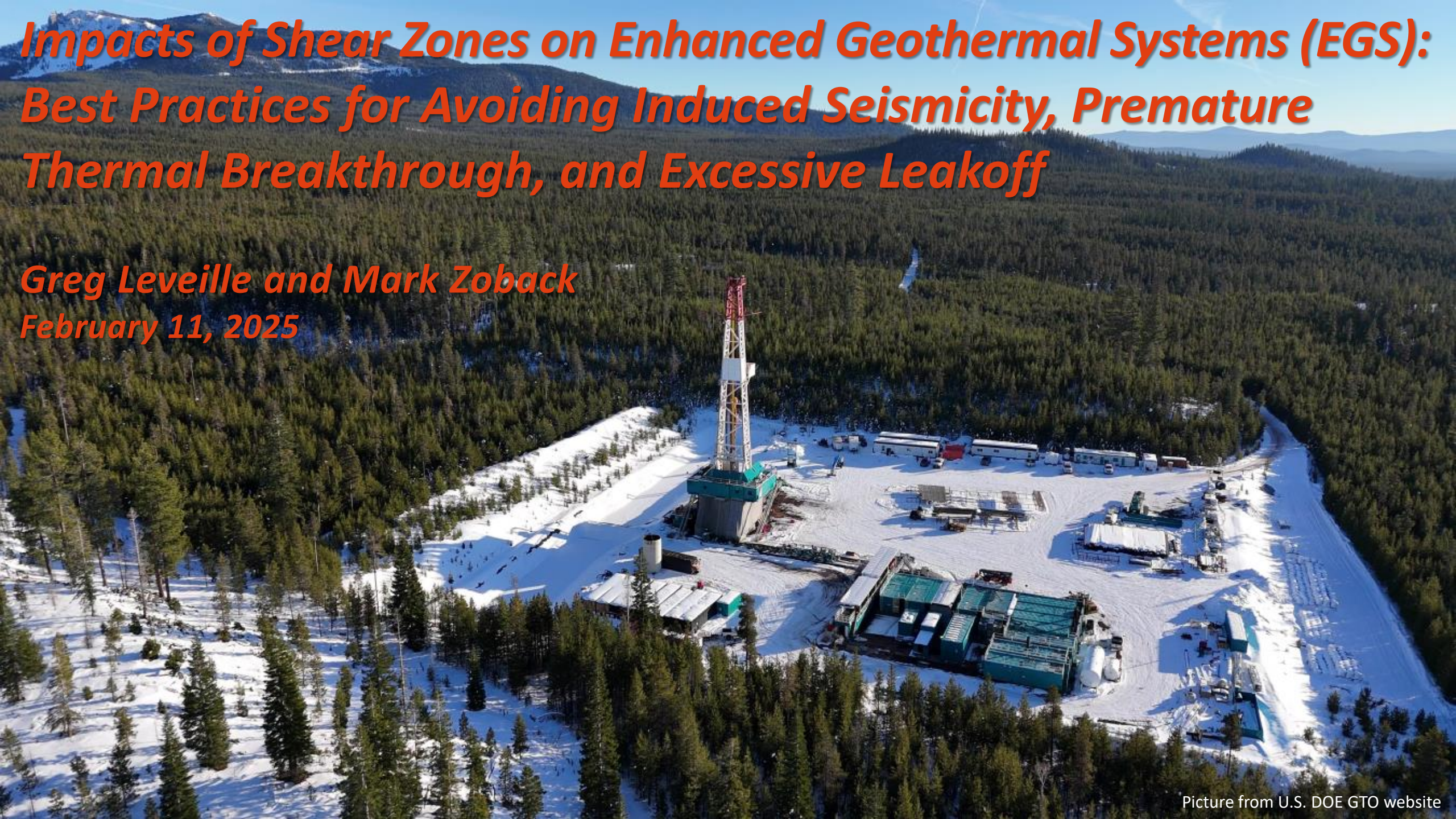

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